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Rolling Resistance Measurements 106 Passenger Car Tires

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Technical Report

Rolling Resistance Measurements 106 Passenger Car Tires

by

Gayle Klemer

August 1981

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16. ABSTRACT

Tires are particularly important in EPA programs since only a small number of the possible vehicle/tire combinations are tested during certification procedures. To the extent that the tires on some production vehicles might have higher rolling resistance than the tires on the EPA certification vehicles, this would contribute to the difference between EPA measured fuel economies and those observed by consumers. If aftermarket replacement tires are significantly different from either the tires used on certification test vehicles or production vehicles this could affect estimation of future petroleum consumption.

This study investigates a diverse range of tires currently available on the replacement passenger car tire market. One hundred-six tires from fifty different model lines were tested. The rolling resistance of these tires are analyzed against other tire characteristics (tire construction, new versus retread, etc.) to gain insight as to the effects of these characteristics on vehicle fuel economy.

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I. Introduction

Energy dissipated by the tires in rolling over the road surface is the major load on the engine at speeds below 40 miles per hour.[1] The exhaust emissions, particularly NOx emissions, and the fuel consumption of the vehicle are strongly affected by the load imposed on the vehicle. In this manner, the rolling resistance of tires affects both exhaust emissions and fuel economy.[2,3]

Tires are particularly important in EPA programs since only a small number of the possible vehicle/tire combinations are tested during certification procedures. To the extent that the tires on some production vehicles might have higher rolling resistance than the tires on the EPA certification vehicles, this would contribute to the difference between EPA measured fuel economies and those observed by consumers. If aftermarket replacement tires are significantly different from either the tires used on certification test vehicles or production vehicles this could affect estimation of future petroleum consumption.

This study investigates a diverse range of tires currently available on the replacement passenger car tire market. One hundred-six tires from fifty different model lines were tested. The rolling resistance of these tires are analyzed against other tire characteristics (tire construction, new versus retread, etc.) to gain insight as to the effects of these characteristics on vehicle fuel economy.

II. Background

In October of 1977, EPA staff members presented the results of a tire rolling resistance study, "Variations in Tire Rolling Resistance - A 'Real World' Information Need," at a joint Society of Automotive Engineers - Department of Transportation conference. This paper presented data indicating significant differences between the rolling resistances, and associated fuel economy effects, of two tire construction types: radial and bias ply. Variations in rolling resistance among radial tires of various manufacturers were also observed.[4]

Other papers presented at this 1977 joint conference and additional later studies by EPA quantified the potential fuel economy savings of low-rolling-resistance tires. A 1979 EPA Technical Report concluded that a two to four percent improvement in vehicle fuel economy occurs using radial rather than non-radial tires [5]. Results from a track test program conducted in 1979 showed a six percent fuel economy improvement using radial tires and a four percent difference in fuel efficiency among radial tires from different manufacturers.[2] Most significantly, this study demonstrated that the tire's rolling resistance is a good predictor of its over-the-road fuel efficiency. These effects are also obser

vable on the EPA dynamometer tests, as are effects on the exhaust gas emissions of the vehicle. A recent EPA program using the dynamometer test methods of the EPA certification program concluded that changing the tires from bias-ply to radial increased fuel economy by about three percent, decreased NOx emissions by 0.12 grams per mile, and tended to decrease CO emissions.[3]

The need for a standard test procedure to systematically test tires and provide low cost, reliable, repeatable results was recognized. Toward filling this need, the development of an EPA Recommended Practice for the rolling resistance testing of tires was begun in 1977. Appendix I is the final "EPA Recommended Practice for Determination of Tire Rolling Resistance Coefficients." This practice was developed over a period of four years, with extensive review and comment by tire and automobile manufacturers, professional societies and individual experts in the field.[6] This Recommended Practice was used to obtain the rolling resistance data presented in this paper. This study demonstrates the value of using the Practice to describe tires currently available to the consumer.

III. Test Matrix Design

To observe the effect of different tire characteristics on tire rolling resistance a 106 tire test matrix was designed to represent the U.S. replacement tire market.[7] Tires were selected from the available brands according to their market shares. We tried to incorporate at least one tire from every manufacturer who had a one percent, or more, share of the market.

The variables which were included in the test matrix to be examined for their relationship to rolling resistance were also selected in proportion to their sales. These variables were, construction type, tread type, body cord material, belt fiber, manufacturer, size, and whether the tire was new or retreaded. Provision was also made to test several tires of the same model, manufactured on different dates, plus several indentical tires, to examine the consistency with which tires are made. Overall, we were able to meet these many diverse demands quite well, however, our sample size of 106 tires is small in comparison with the number of tires sold in 1980, 157 million tires. Selection of the tires, although based on the market shares, was influenced by the limitations of the sample size, tire availability, and the need to provide for accurate statistical analysis. Appendix II compares the percentage representation in the replacement market and in our test matrix.

IV. Test Procedure and Equipment

The test procedure used was the "EPA Recommended Practice for Determination of Tire Rolling Resistance Coefficients (Appendix

I)." Professor Samuel Clark of the University of Michigan directed the testing under an EPA contract.

The tests were run on a 67.3-inch diameter tire dynamometer, using the torque method. A brief discription of the test procedure follows. The tire was first mounted on a vehicle and run for 50 miles on a large single-roll dynamometer. This break-in period allowed any possible permanent growth to take place, without affecting the test. Once the tire was broken in, it was mounted on the test rim and inflated to the proper pressure and the circumference measured. The tire was mounted on the moveable carriage of the machine and loaded against the test drum to 80 percent of its T.R.A. design load. To achieve equilibrium the tire was run at 50 miles per hour for 45 minutes. At this point the tire was ready for the actual test measurement. First the vertical load was checked to ensure it was still at 80 percent of its T.R.A. design load and then a torque reading was taken. Also at this time the carriage travel was recorded (to determine the amount of deflection under load). A skim reading was then taken with the vertical load reduced to ten pounds. Finally, the inflation pressure and tire circumference were measured again. Appendix III is a sample data sheet. (For more detailed information on the procedure see Appendix 1.)

Inflation pressure was measured to $\pm$0.1 p.s.i. on a dial gauge. Vertical load was measured by an electric load cell and recorded on a Hewlett-Packard x-y plotter. The torque was measured, accurate to $\pm$10 inch-pounds, with a torque cell and displayed digitally. Speed was kept constant at 50 miles per hour, within 1/4 mile per hour, measured by a counter and displayed digitally. Ambient temperature was kept between 70° and 80°F, and measured with a Fluke digital thermometer.

V. Data Reduction

Below are the steps used to determine the rolling resistance coefficient from the raw data:

1. The net test wheel drive torque (T) is the torque measured during the test (Tx) minus the skim torque (Tp)

$$T = T_x - Tp \qquad (1)$$

This takes into account the parasitic losses associated with the test machine.

2. The rolling resistance force (R.R.) is the net torque divided by the test wheel radius (33.65 inches).

$$R.R. = T/R \qquad (2)$$

3. The rolling resistance force is normalized from the test temperature to 75°F by:

$$R.R.^* = \frac{R.R.}{1 + c_t(t_x - t_s)} \quad (3)$$

where:

$R.R.^*$ = rolling resistance force at the standard temperature,

$R.R.$ = rolling resistance force from eqn. 2,

c_t = temperature correction coefficient:

$5 \times 10^{-3}/°F$ or $9 \times 10^{-3}/°C$,

t_x = measured test temperature,

t_s = standard temperature: 75°F or 24°C.

4. The net load (L) is the load during the test (L_x = 80 percent T.R.A. design load for the tire) minus the skim load (Lp = 10 lbs).

$$L = L_x - L_p \quad (4)$$

5. The rolling resistance coefficient (RRC) is the net rolling resistance force at standard temperature (R.R.*) divided by the net load (L).

$$R.R.C. = R.R.^*/L \quad (5)$$

Appendix IV lists all 106 tires tested and their rolling resistance coeffients while Appendix V contains the data and the result of data reduction for each tire tested.

VI. Statistical Analysis Relating Rolling Resistance to Other Tire Characteristics

The data from the rolling resistance tests of 106 tires was analyzed to learn which tire characteristics seem to affect rolling resistance. An analysis of variance (ANOVA) was done for each of the following tire characteristics to compare the mean rolling resistance of each of the different construction types, body cords, belt fibers, tread types, nominal diameters, and manufacturers. An ANOVA was also done to observe whether the condition of the tire, new versus retreaded, affects the mean rolling resistance. To investigate the consistency of tire manufacture as it affects rolling resistance we compared the means of two groups of tires, from each of two model lines, manufacturered at least one week apart. We also compared the means of three different groups of identical (same model, tread, week of manufacture, etc.)

tires. Finally, we performed a linear regression between purchase price and rolling resistance to determine whether the price of a tire is related to its rolling resistance.

When interpreting the results of these analyses, the sample-to-population size ratio must be considered. A 106-tire sample is relatively large for an engineering sample tested with high data precision, hence, high confidence values were usually obtained. However, the sample size is quite small compared to the total population of annual tire sales, 157 million. So, while strong statistical conclusions are often obtained from the sample, the validity of extrapolating these conclusions to the entire population is very dependent upon the representativeness of the sample.

Construction Type

We tested tires from three construction types, radial-ply, bias-belted, and bias-ply, in each of three nominal diameters: 13-, 14-, and 15-inches. In the 13- and 15-inch sizes we observed a relationship between construction type and rolling resistance, with 99.99 and 99.56 percent confidence, respectively. The terms "percent confidence" and "confidence level" are used, here and elsewhere in this paper, in the rigorous statistical sense. That is, in this case sufficient sample information exists to simply state the probability that the rolling resistance data of the different tire groups did not originate from a common population. Stated negatively, there is less than one minus this confidence probability that the rolling resistance data obtained from a single distribution would show these results. (For example, for an ANOVA with a confidence level of 99 percent the probability that the data came from a single distribution is 1-.99 = .01 or 1%.) The rolling resistance mean of radial ply tires was 18.3 percent lower than both the mean of bias-belted tires and the mean of bias ply tires, in the 13-inch size. When interpreting these results, it should be noted that the distribution of the data from one tire type may overlap the distribution of the other types. For example, there were 5 bias-belted and 5 bias ply models that had lower RRC's than at least one radial model (see Appendix IV). In the case of 15-inch tires the rolling resistance mean of radials was 27.5 percent lower than that of bias-belted tires and 23.5 percent lower than that of bias ply tires. The number of 14-inch tires we tested (4) was insufficient to perform a meaningful analysis of variance.

Body Cord

Among 13-inch nominal diameter steel-belted radials we tested tires of two different body cords: polyester and rayon. We found the difference in the rolling resistance means of these two groups was statistically insignificant; in this sample the type of body cord used in the tire does not seem to affect rolling resistance.

Comparisons to test for the affect of body cord on rolling resistance could not be made for any other size or type of tire,

because all other tires in the test matrix were made exclusively with polyester body cord.

Belt Fiber

Among 13-inch nominal diameter radials, we tested tires made with four different belt materials: steel, fiberglass, aramid, and rayon. In our sample we observed, with 99.14 percent confidence, that a relationship did exist between the type of belt material in the tire and its rolling resistance. Fiberglass-belted radials had the lowest mean rolling resistance (RRC= 0.01108), followed by steel-belted (RRC=0.01162), aramid-belted (RRC=0.01232), and lastly rayon-belted (RRC=0.01462) radials. However, it should be noted that while fiberglass-belted radials had the lowest mean RRC, the single tire model with the lowest RRC was steel-belted, which, along with the small difference in the steel and fiberglass means (0.00054), indicates a possible overlap of the population distributions.

Tread Type

We tested three tread types on 13-inch steel-belted radials: conventional highway tread, mud and snow tread, and year-round all-weather tread. We observed a relationship between the type of tread used on these tires and the rolling resistance, at a 95.83 percent confidence level. Conventionally-treaded steel radials had a mean rolling resistance 21.0 percent lower than the one with mud and snow tread, and 5.6 percent lower than those with year round tread, however, the year-round model had a lower RRC than 9 conventionally-treaded steel radial models. This demonstrates the potential overlap between RRC distributions and the necessity of viewing the high confidence level with caution.

When we included fiberglass-belted 13-inch radials (which all had conventional tread) in the sample and repeated the analysis we were able to compare the effect of tread type to the effect of belt fiber on rolling resistance. Comparing the eta-squared correlation ratio from each ANOVA we observed that the choice of belt material is more important to rolling resistance than the choice of tread type. Belt fiber accounts for 25.6 percent of the variability in the rolling resistance in this sample, while tread type accounts for 16.5 percent.

We also tested 13-inch (new) bias-ply tires with conventional and mud/snow treads. In this sample we observed, with 99.99 percent confidence, a relationship between the type of tread on the tire and the rolling resistance. The mean rolling resistance of conventionally-treaded bias-ply tires was lower than the mean of those with a mud/snow tread by 15.6 percent. However, when the same analysis was performed for 13-inch retreaded bias-ply tires we could not reject the equality-of-means hypothesis between conventional and mud/snow treads at the 95 percent confidence level.

We could make no tread type comparison for bias-belted tires or for other size groups since all of the other tires in our test matrix had a conventional tread.

Retreaded versus New Tires

The test matrix contained three groups within which we could compare retreaded tires to new tires: 13-inch bias-ply tires with conventional tread, 13-inch bias-ply tires with mud/snow tread, and 15-inch steel-belted radial-ply tires. In the first and last groups we observed a relationship between the condition of the tire, new versus retreaded, and the rolling resistance, with over 95 percent confidence. New 13-inch conventional bias-ply tires had a mean rolling resistance 15.4 percent lower than their retreaded counterparts, while the rolling-resistance mean for new 15-inch steel-belted radials is 24.8 percent lower than the mean for retreaded steel radials (however, the new tires were Goodyear Arriva, which had the lowest mean RRC of any tires we tested). We could not reject the rolling resistance equality-of-means hypothesis for the new/retreaded bias-ply snow tire comparison at the 95 percent confidence level.

Nominal Diameter

Our test matrix contained 13-, 14-, and 15-inch nominal diameter tires in each of the three construction types: radial-ply, bias-belted, and bias-ply. We did not observe a statistically significant relationship between the tire diameter and RRC for any of these groups. However, when we corrected our data for the curvature of the test wheel by using the SAE flat-surface approximation,[8] we observed a relationship been diameter and RRC, at the 99 percent confidence level, for radial-ply tires. (Again, these high confidence factors should be vieved with some reserve due to the size of the sample relative to the population.) The 15-inch diameter radials had the lowest mean RRC (flat-surface corrected), 1.0 percent lower than the 14-inch radials and 13.6 percent lower than the 13-inch radials. In the cases of biasbelted and bias ply tires we could not reject the RRC equalityof-means hypothesis applied to the three diameters. However, in both of these groups a trend exists towards decreasing (flatsurface corrected) RRC with increasing nominal diameter.

Manufacturer

Out of 106 tires in our test matrix twelve of them were retreaded tires and another eight were tires with special-purpose treads. The remaining 86 were all new tires with a conventional highway tread, but were of mixed construction, size, belt material, etc. Through an analysis of variance of these tires we observed that there is a connection between manufacturer and tire rolling resistance. This observation was made with 96.6 percent confidence, but is subject to the limitations of the small sample.

In all we tested tires from 19 companies. The manufacturers with the five lowest mean rolling resistances were Goodyear (RRC = 0.01169), Michelin (RRC = 0.01194), Delta (RRC = 0.01242), Uniroyal (RRC = 0.01260), and Montgomery Ward (RRC = 0.012855).

Rolling Resistance Consistency Over Time

Three groups of a bias-ply model and two groups of a fiberglass-belted radial were designed such that they were identical except for the fact that they were manufactured on different dates (as indicated by the DOT tire identification mark).

Of the three groups from the bias-ply model line one group was made during each of the following weeks: August 12-18, 1979, August 17-23, 1980, and August 31-September 6, 1980. The greatest difference among the groups' means is 0.0032 (between the two groups made in 1980), while the pooled standard deviation (the square root of the pooled variance) for these three groups is 0.00026. Of the two groups from the fiberglass-belted radial model line, one was made during April 27-May 3, 1980 and the other during May 4-10, 1980. The difference between the means of these two groups is 0.00001, while the pooled standard deviation is 0.00025. These figures indicate very consistant rolling resistance for these two model lines. This means we can rely on the rolling resistance test results as a good predictor of the rolling resistance of any tire from that particular model line. The groups and their means and standard deviations are presented in Table 1.

Rolling Resistance Consistency Within Groups of Identical Tires

Three groups of tires were tested which, within themselves, were identical in every way (construction, manufacturer, week of manufacture): one group of steel-belted radials, one of bias-belted tires, and one of bias-ply snow tires. The standard deviations of these groups were 0.00038, 0.00017, and 0.00054, respectively. This again points out the predicability of rolling resistance for an individual tire if a tire of the same model has been tested. (This information is summarized in Table 2).

Price

We were curious to know whether the price of a tire was related to its rolling resistance. We performed a linear regression of price against rolling resistance for each of the three construction types separately. (We included only 13-inch, new, conventional tires in this analysis). We observed in all three cases that price is not linearly dependent on rolling resistance. Rolling resistance accounts for only 6.2 percent of the variability in the price of radials, 6.7 percent of the variability in the price of bias-belted tires and 3.0 percent of the variability in the price of bias-ply tires. These results agree with an earlier analysis done by an EPA staff member.[9]

Other Characteristics Investigated

Of the 106 tires we tested, 19 models were labeled with UTQG grades. Table 4 lists those tires, their three UTQG grades and their RRC's (or mean RRC if more than one tire of that model was tested). This table illustrates that rolling resistance coefficients also do not seem to correlate with any of the DOT-UTQG grades: treadwear, traction, or temperature.

We also tried to analyze the affect of section width and aspect ratio on rolling resistance. In both cases we found we did not have a sample that varied enough in either of these areas to make a valid analysis possible. Also, we were not able to test the effect of different rubber compounds on rolling resistance. We had no non-destructive method by which we could determine the rubber compound used in each tire. The rubber compound may be a "hidden factor" which might account for some of the correlation between rolling resistance and the other tire characteristics. The results of Section VI are summarized in Table 3.

VII. Conclusion and Summary

In this 106 tire test program a strong correlation exists between tire rolling resistance and tire construction type, the belt fiber used, the tread type, the condition of the tire (new vs. retreaded), the nominal diameter (on a flat surface), and the manufacturer of the tire. No significant correlation seems to exist between rolling resistance and the choice of body cord, or original purchase price of the tire. Caution should be used when carrying these conclusions over to the general population of tires. We feel our sample is highly representative of the market, however, it is a small sample in comparison to its population.

Among the 76 13-inch tires in this study the mean rolling resistance of radial ply tires is 18 percent lower than that of bias-belted tires and bias-ply tires, however, there were 5 bias-belted and 5 bias ply models with lower RRCs than the highest-RRC radial model.

The mean rolling resistance of fiberglass-belted radials is about 5 percent lower than that of the steel-belted radials, 10 percent lower than that of aramid-belted radials, and 24 percent lower than that of the rayon-belted radial. Exceptions to the mean were 2 steel-belted models that had lower RRCs than the lowest-RRC fiberglass model.

Mean rolling resistance of conventionally-treaded steelbelted radials is 21 percent lower than that of mud and snow treads, while the same comparison for bias ply tires is about 16 percent.

New tires had 15-25 percent less rolling resistance than retreaded tires.

In general, the statistical analysis indicates that the optimal fuel-saving tire would be a new fiberglass-belted radial with conventional tread; yet the model with the lowest mean RRC was a steel-belted radial. Steel and fiberglass radial models constitute 98 percent of the original equipment tires sold on new cars in 1980. To the extent that a higher percentage of replacement tires are high-rolling-resistance tires there may some fuel economy loss when the original tires are replaced. This analysis could not include effects of different rubber compounds on rolling resistance, therefore these effects are a "hidden factor" which may influence the statistics.

Since a distinct causual relationship was not observed between the tire construction type, belt fiber, etc., and the tire rolling resistance we conclude that rolling resistance coefficient itself is the best tire characteristic by which to judge a tire model's fuel efficiency. The rolling resistance coefficient of tires of the same model seem constant both for tires manufactured during the same week and during different weeks. Therefore, RRC appears to be a sufficiently stable parameter to be used to grade tire model lines consistantly.

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Table 1

$\overline{RRC}$ and s of Groups of Tires Manufactured During Different Weeks

Bias Ply

Group 1 Aug. 12-18, 1979	Group 2 Aug. 17-23, 1980	Group 3 Aug. 31-Sept. 6, 1980
N = 2	N = 2	N = 6
$\overline{RRC}$ = 0.01343 s = 0.00024	$\overline{RRC}$ = 0.01354 s = 0.00006	$\overline{RRC}$ = 0.01322 s = 0.00029

Fiberglass-Belted Radial-Ply

Group 1 April 27-May 3, 1980	Group 2 May 4-10, 1980
N = 3	N = 3
$\overline{RRC}$ = 0.01071 s = 0.00035	$\overline{RRC}$ = 0.01070 s = 0.00007

Table 2

$\overline{RRC}$ and s of Groups of Identical Tires

Steel-Belted Radial Model

N = 7
$\overline{RRC}$ = 0.01006
s = 0.00038

Bias-Belted Model

N = 3
$\overline{RRC}$ = 0.01295
s = 0.00017

Bias-Ply Snow Tread Model

N = 3
$\overline{RRC}$ = 0.01755
s = 0.00054

Table 3

Summary of Effects of Tire Characteristics On Rolling Resistance

Tire Characteristics	Sample Used	Result Observed
Construction type	New 13-inch conv. tires	Radials had 18.3% lower RRC than bias-belted and bias-ply tires.
	New 14-inch conv. tires	None - not enough data.
	New 15-inch conv. tires	Radials had 27.5% lower RRC than bias-belted and 23.5% lower RRC than bias-ply tires.
Body Cord	New-13 inch steel radials	Does not affect RRC
Belt Fiber	New 13-inch radials	Fiberglass had 4.7% lower RRC than steel, 10.1% lower RRC than aramid and 24.2% lower RRC than rayon.
Tread Type	New 13-inch radials	Conventional tread had 21.0% lower RRC than mud/snow and 5.6% lower RRC than year-round treads.
	New 13-inch bias ply	Conventional tread had 15.6% lower RRC than mud/snow.
	13-inch bias ply retreads	No significant relationship between tread type and RRC.
Retread/New	13-inch bias ply conventional tread	New tires had 15.4% lower RRC than retreads.

Table 3 (cont'd)

Summary of Effects of Tire Characteristics On Rolling Resistance

Tire Characteristics	Sample Used	Result Observed
Retread/New (cont'd)	13-inch bias ply mud/snow tread	Condition does not affect $\overline{RRC}$
	15-inch steel radials conventional tread	New radials had 24.8% lower $\overline{RRC}$ than retreads.
Diameter ($\overline{RRC}$'s corrected for flat-surface approximation)	New radials	15-inch radials had 1% lower $\overline{RRC}$ than 14-inch and 13.6% lower $\overline{RRC}$ than 13-inch radials.
"	New bias-belted tires	$\overline{RRC}$ difference between sizes is not statiscally significant, but there is a tendency for $\overline{RRC}$ to decrease as diameter increases.
	New bias ply	$\overline{RRC}$ difference between sizes is not statiscally significant, but there is a tendency for $\overline{RRC}$ to decrease as diameter increases.
Manufacturer	86 new tires from 19 companies; conventional tread	Identity of the manufacturer does affect $\overline{RRC}$.
$\overline{RRC}$ consistency over time	3 groups of one model of bias ply tire made on different dates	$\overline{RRC}$ of a model does not vary appreciably with date of manufacture.
	2 groups of one model of fiberglass radial made on different dates	$\overline{RRC}$ of a model does not vary appreciably with date of manufacture.

Table 3 (cont'd)

Summary of Effects of Tire Characteristics On Rolling Resistance

Tire Characteristics	Sample Used	Result Observed
RRC consistency within a group of identical tires	A group of 8 identical steel radials	RRC does not vary appreciably (low standard deviation).
	A group of 3 identical bias-belted tires	RRC does not vary appreciably (low standard deviation).
	A group of 3 identical bias-ply snow tires	RRC does not vary appreciably (low standard deviation).
Price	New 13-inch radials	Price is not linearly dependent on rolling resistance.
	New 13-inch bias-belted	Price is not linearly dependent on rolling resistance.
	New 13-inch bias ply	Price is not linearly dependent on rolling resistance.

Table 4

DOT-UTQG Grades Compared to RRC for 19 Tires

Tire	UTQG Grades			RRC
	Treadwear	Traction	Temperature	
Armstrong Coronet X/A	140	B	C	0.01222
Armstrong Power King	70	B	C	0.01641
Dunlop Gold Seal	100	A	C	0.01326
Firestone Deluxe Champion Polyester	80	B	C	0.01518
B.F. Goodrich Belted CLM	100	A	C	0.01506
Goodyear Arriva	180	B	C	0.01019
Goodyear Cushion-Belt	100	B	C	0.01295
Goodyear Powerstreak	80	B	C	0.01336
Goodyear Viva	120	B	C	0.01073
Kelly-Springfield Benchmark	70	B	C	0.01375
Kelly-Springfield Navigator	120	B	C	0.01250
K-Mart KM Radial Plus	180	B	C	0.01305
K-Mart KM 78	80	B	C	0.01582
J.C. Penney El Tigre 278	130	B	C	0.01543

Table 4 Cont'd

DOT-UTQG Grades Compared to RRC for 19 Tires

Tire	UTQG Grades			RRC
	Treadwear	Traction	Temperature	
Montgomery Ward Gas Miser	180	B	C	0.01159
Montgomery Ward Runabout	50	B	C	0.01354
Sears Dynaply 24	80	A	C	0.01477
Uniroyal Royal Seal	220	B	B	0.01137
Uniroyal Fastrax	110	B	B	0.01383

ATTACHMENT I

EPA Recommended Practice for Determination of Tire Rolling Resistance Coefficients

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Amended August 1980

Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air, Noise and Radiation
U.S. Environmental Protection Agency

I. Introduction

This test procedure determines the tire rolling resistance coefficient for a free rolling tire at a steady speed. This procedure conforms to the SAE Recommended Practice, Rolling Resistance Measurement Procedure for Passenger Car Tires - SAE J1269, generally adopting the recommended conditions of J1269 as the required standard conditions. The SAE Recommended Practice J1269 and the accompanying SAE information report J1270 may be consulted for additional information.

II. Test Equipment

The test equipment required is a tire dynamometer which measures the tire energy dissipative force as the tire is driven by a large cylindrical test wheel.

A. Tire Dynamometer

The test dynamometer shall be a cylindrical surface machine of 67.23 in (1.7076m) diameter. The test machine shall be capable of supplying a force on the tire perpendicular to the test surface, and shall be able to measure the transverse reaction forces acting on the tire or the torque necessary to drive the test wheel. During this process the machine must be capable of maintaining the test surface at constant speed. The width of the test surface must exceed the width of all test tires, and the test surface shall be coated with a medium coarseness abrasive (80 grit). As an example, medium grit 3M Safety-Walk represents a satisfactory surface.*

1. Test Machine Alignment

The direction of application of the tire load must be normal to the test surface within 0.03 deg (0.5 mrad). The wheel plan of the tire must be normal to the test surface within 0.03 deg (0.5 mrad) and parallel to the direction of motion of the test surface within 0.03 deg (0.5 mrad).

2. Test Machine Control Accuracy

Exclusive of perturbations induced by the tire and rim nonuniformities, the test equipment must control the test variables within the following limits:

	U.S. Customary Units	SI Units
Tire Load	5 lbf	22 N
Surface Speed	1 mph	2 km/h

* The manufacturer of this product is identified to clarify the example and does not imply endorsement of the product.

3. Test Machine Instrumentation Accuracy

The instrumentation used for readout and recording of test data must be accurate within the following tolerances:

	U.S. Customary Units	SI Units
Tire Load	2 lbf	8 N
Surface Speed	0.5 mph	0.8 km/h
Spindle Force	0.1 lbf	0.4 N
Loaded Radius	0.1 in	0.002 m

B. The Test Cell Requirements

The primary requirement for the test cell is that the ambient temperature be well controlled. In addition, the support services of compressed air should be available for tire inflation as should the necessary gauges to measure tire inflation.

1. Thermal Control

The ambient temperature in the vicinity of the test tire shall be 75 ± 5°F (24 ± 3°C).

2. Temperature Measurement Precision

The instrumentation used to measure the ambient temperature must be accurate to within 1 °F (0.5 °C). This instrumentation shall be located approximately 15 inches from the tire, measured perpendicular to the sidewall.

III. Test Procedure

The test procedure consists of the following steps: tire mounting; tire break-in; equilibration of the tire to the test ambient temperature; adjustment of the cold inflation pressure; tire warm-up and then measurement of the tire rolling resistance.

A. Tire Mounting

1. Rims

The tire shall be mounted on test rims which have an approved contour and width as specified by the Tire & Rim Association, Inc., as "design rim width" ± one half inch for the size tire being rested. For tire sizes not standardized by the Tire & Rim Association, Inc., reference should be made to the appropriate standardizing organization as listed in the Federal Motor Vehicle Safety Standards (CFR Title 49 §571.109 Table I). These rims shall have a maximum radial runout of 0.035 in (0.88 mm) and a maximum lateral runout of 0.045 in (1.1 mm).

2. Inflation Pressure

The inflation pressure of the tires after mounting shall be:

Alpha Numeric Size Tires	32 psi (220 kPa)
"P" Type tires	35 psi (240 kPa)

The tire inflation pressure after mounting shall be correct to within 1 psi (6.8 kPa). The gauges used to measure this tire inflation pressure shall be accurate to within 0.5 psi (3.4 kPa).

B. Tire Break-in

Tires may undergo significant permanent growth upon first operation and therefore may require an initial break-in and cooling period prior to the start of the test. A break-in run consisting of installing the tire on the tire test machine and operating the system under the test conditions for a period of 1 hour is recommended.

C. Thermal Conditioning

After initial break-in the tire shall be placed in the thermal environment of the test conditions for a minimum period of 3 hours before the test. During this period the tire inflation pressure should be checked and adjusted if necessary, to the design cold inflation pressure of the tire.

D. The Rolling Resistance Measurement

The test consists of a final pressure check, loading the tire, the tire warm-up, during which the tire temperature and inflation are allowed to increase as they would in typical service; followed by the rolling resistance measurement.

1. Installation on the Test Machine

The inflation pressure of the tire shall be checked and adjusted if necessary. The inflation pressure immediately prior to the test shall be correct to within 0.25 psi (1.7 kPa). The gauges used to determine this pressure shall be accurate to within 0.25 psi (1.7 kPa). The tire shall then be installed on the test machine if not already installed, and the load on the tire perpendicular to the test surface shall be adjusted to 80 percent of the design load of the tire.

2. Tire Warm-up

The test tire shall be conditioned by operation at a speed of 50 mph for a minimum of 45 minutes.

T_x = the test wheel drive torque of III D3.

T_p = the parasitic test wheel drive torque of III D4.

B. Tire Energy Dissipation Force

The tire energy dissipation force shall be calculated from the net spindle reaction force by the following equation:

$$F_d = f(1 + r/R) \quad (2)$$

Where:

F_d = the tire energy dissipation force lb (N),

F = the net tire spindle force lb (N),

r = the tire loaded radius, in (m),

R = the test surface radius, in (m).

In the case of the torque measurement method the energy dissipation force is to be calculated by:

$$F_d = T/R \quad (3)$$

3. Rolling Resistance Measurements

Following the tire warm-up and with the test dynamometer operating at 50 mph, the following parameters shall be recorded:

a. Tire spindle force or test wheel drive torque.
b. Normal load on the tire.
c. Loaded radius of the tire.

4. Measurement of Parasitic Losses

As a final measurement, the parasitic machine losses shall be determined. The test machine speed shall be maintained at 50 mph while the load onthe tire is reduced to approximately one percent of the test load. Under this condition the following parameters shall be determined:

a. Tire spindle force or test sheel drive torque.
b. Normal load on the tire.

IV. Data Analysis

The data reduction consists of the correction for the machine parasitic losses, conversion to a tire energy dissipation force, correction to the standard test temperature, and the computation of the tire rolling resistance coefficient.

A. Subtraction of Parasitic Losses

The spindle force or test wheel drive torque measurement of the machine parasitic losses obtained in III. D4, shall be subtracted from the spindle forces or test wheel drive torques measured during the test, III. D3, to obtain the net spindle reaction force or net drivewheel drive torque.

That is:

$$F = F_x - F_p \quad (1)$$

$$T = T_x - T_p$$

Where:

F = the net spindle reaction force.

F_x = the spindle reactive force measured during the test, III. D3.

F_p = the parasitic spindle reactive force of III. D4.

T = the net test wheel drive torque.

C. Temperature Correction

The tire energy dissipation force shall be corrected to the standard test temperature of 75°F by the following equation:

$$F_d^* = F_d[1 + c_t(t_x - t_s)] \quad (4)$$

F_d^* = the tire dissipative force at the standard temperature,

t_x = the average measured temperature over the duration of the test,

t_s = the standard test temperature 75°F (24°C),

c_t = the temperature correction coefficient, 5×10^{-3}/°F (9×10^{-3}/°C).

The test ambient temperature shall always be within 75° ± 5°F (24 ± 3°C), as described in II.B.1.; therefore, this linear temperature correction will always be applied over a temperature range of less than 5°F (3°C) for any one test.

D. Net Load Force

The parasitic load force measured in III D4 shall be subtracted from the normal load force measured during the test IIID3 to obtain the net load force.

That is:

$$L = L_x - L_p \tag{5}$$

Where:

L = the net load force,

L_x = the tire load force measured during the test III D3.

L_p = the tire load force during the parasitic measurement III D4.

E. Rolling Resistance Coefficient

The rolling resistance coefficient is calculated by dividing the energy dissipation force by the net load imposed in the tire:

$$C = F_d^*/L \tag{6}$$

Where:

C = rolling resistance coefficient (RRC).

Equations 1, 2, 4, 5, and 6 may be combined into the following single equation:

$$C = \frac{(F_x - F_p)(1 + r/R)[1 + c_t(t_x - t_s)]}{(L_x - L_p)} \tag{7}$$

Likewise, equations 1, 3, 4, 5, and 6 may be combined as:

$$C = \frac{(T_x - T_p)[1 + c_t(t_x - t_s)]}{R(L_x - L_p)} \tag{8}$$

Appendix II

Comparison Between Replacement Tire Market* and Test Matrix

New Tires (all 13-inch tires)

	% Sales	% Matrix
Radials	53.0	54.5
Polyester cord	92.0	89.1
Rayon cord	8.0	10.9
Steel belt	71.6	63.0
f.g. belt	18.3	30.4
Aramid belt	4.0	4.3
Rayon belt	6.2	2.2
Conventional tread	79.3	93.5
Mud/snow tread	15.8	2.2
Year-round tread	4.9	4.3
Bias belted	17.0	13.1
Polyester cord	100.0	100.0
Steel belt	1.4	0.0
f.g. belt	98.0	100.0
Rayon belt	0.6	0.0
Conventional tread	79.3	100.0
Mud/snow tread	15.8	0.0
Bias ply	30.0	32.1
Polyester cord	98.0	100.0
Nylon cord	2.0	0.0
Conventional tread	79.3	81.5
Mud/snow tread	15.8	18.5
Retreads	17.7	11.3
Radials	12.0	33.3
Bias-belted	40.0	0.0
Bias ply	48.0	66.7
Conventional tread	55.2	50.0
Snow tread	41.4	50.0
Year-round tread	3.4	0.0

* "MTD's 14th Annual Facts/Directory"; Modern Tire Dealer, January 28, 1980.

Appendix II (cont'd)

Manufacturers	% Sales		% Matrix
Goodyear	14.0		38.1*
Firestone	10.5		13.1
Sears	10.0		8.3
Michelin	5.0		4.8
Wards	5.0		4.8
BFG	4.5		3.6
Kelly-Springfield	3.0		2.4
K-Mart	3.0		2.4
Atlas	3.0		2.4
Uniroyal	3.0		2.4
JCP	3.0		2.4
General	3.0		2.4
Dunlop	3.0		2.4
Dayton	2.2	not available	-
Delta	1.5		2.4
Cooper	1.3		2.4
Armstrong	1.2		2.4
Remington	1.0	not available	-
Multi-Mile	1.0		1.2
Hercules	1.0		1.2
Discount	-		1.2

* Extra Goodyear tires were obtained to test several other variables while the manufacturer remains constant.

Larger Sizes (chosen from the lists of most popular sizes)

P195-75R14
P215-75R14
P215-75B14
P225-75R15
P225-75B15
P215-75R15
P215-75B15
H7815
HR7815
G7815
GR7815
G7814

APPENDIX III

SAMPLE DATA SHEET

EPA - ID _____ UM - ID _____

TIRE ROLLING RESISTANCE

University of Michigan Ann Arbor, Michigan

Date _____

Tire Size _____ Load Range _____

Brand Name _____ Manufacturer _____

D.O.T. Number _____ Construction _____

Other Markings _____ Condition _____

Test Rim and Contour _____

_____

_____

Capped Air _____ Regulated Air _____

Cold Inflation Pressure _____

Radial Load _____

Ambient Temperature _____

Final Inflation Pressure _____

Tire Circumference _____

Loaded Radius _____

_____

_____

Test Wheel Diameter 67.23 in. Wheel Speed 50 mph

Wheel Surface 80 Grit

_____

_____

Equlibrium Rolling Resistance 67-In. Dia. Wheel _____

Temperature Corrected Rolling Resistance _____

Rolling Resistance Coefficient _____

APPENDIX IV

Rolling Resistance Coefficients for 106 Tires from a Recent EPA Tire Test Program

Tires are listed in order of increasing rolling resistance within their construction groups.

Tire	Size	RRC	Comments
RADIAL			
Goodyear Arriva	P185-80R13	.00971	Polyester Cord/Steel belt
"	P225-75R15	.00972	"
"	P185-80R13	.00981	"
"	"	.00982	"
"	P215-75R14	.00985	"
"	P185-80R13	.00993	"
"	"	.00997	"
B.F. Goodrich Lifesaver XLM	P185-80R13	.01027	Polyester cord/steel belt
Goodyear Viva	P185-80R13	.01040	Polyester cord/glass belt
Goodyear Arriva	P195-75R14	.01050	Polyester cord/steel belt
Goodyear Viva	P185-80R13	.01051	Polyester cord/glass belt
Goodyear Arriva	P185-80R13	.01055	Polyester cord/steel belt
"	P215-75R15	.01058	"
"	P185-80R13	.01065	"
Goodyear Viva	P185-80R13	.01065	Polyester cord/glass belt
"	"	.01065	"
"	"	.01066	"
"	"	.01078	"
Sears Guardsman	P185-75R13	.01088	Polyester cord/glass belt
"	"	.01099	"
Goodyear Viva	P185-80R13	.01109	Polyester cord/glass belt
"	"	.01110	"
Goodyear Arriva	P155-80R13	.01110	Polyester cord/steel belt
Firestone Deluxe Champion Radial	P175-80R13	.01114	Polyester cord/glass belt

APPENDIX IV (Cont'd)

Tire	Size	RRC	Comments
RADIAL			
Uniroyal Royal Seal	P185-80R13	.01137	Polyester cord/steel belt
Delta Sierra GBR	BR78-13	.01159	Polyester cord/glass belt
Discount Arizonian	P175-80R13	.01159	Polyester cord/steel belt
Montgomery Ward Gas Miser	P185-80R13	.01159	Polyester cord/steel belt
Michelin XZX	P175-75R13	.01171	Rayon cord/steel belt
"	"	.01190	"
Firestone Radial Retread	HR78-15	.01195	Polyester cord/steel belt retread
Goodyear American Eagle	P185-75R13	.01196	Polyester cord/aramid belt
Michelin XZX	P175-75R13	.01207	Rayon cord/steel belt
"	"	.01208	"
Armstrong Coronet X/A	P185-75R13	.01222	Polyester cord/glass belt
Firestone Trax 12	P185-75R13	.01222	Polyester cord/steel belt
Cooper Trendsetter	P185-75R13	.01239	Polyester cord/glass belt
Firestone Trax 12	P185-75R13	.01240	Polyester cord/steel belt
Atlas Goldenaire II	P185-75R13	.01242	Polyester cord/steel belt
General Dual Steel II	BR78-13	.01250	Polyester cord/steel belt
Kelly Navigator	P185-75R13	.01250	Polyester cord/steel belt
Firestone 721	P175-75R13	.01262	Polyester cord/steel belt
Mont. Ward Grappler E'lire	P185-75R13	.01268	Polyester cord/aramid belt
Sears Roadhandler	BR78-13	.01270	Polyester cord/steel belt
Penney Mileagemaker XP	P185-80R13	.01274	Polyester cord/steel belt
Firestone Radial Retread	HR78-15	.01283	Polyester cord/steel belt retread
Firestone 721	P175-75R13	.01294	Polyester cord/steel belt
Dunlop Elite 70	P195-70R13	.01298	Polyester cord/steel + nylon belt
K-Mart KM Radial Plus	P185-75R13	.01305	Polyester cord/steel belt

APPENDIX IV (Cont'd)

Tire	Size	RRC	Comments
RADIAL			
Sears Roadhandler	BR78-13	.01354	Polyester cord/steel belt
Hawk	GR70-15	.01454	Polyester cord/steel belt retread
B.F. Goodrich T/A Mark	P175-70R13	.01462	Rayon cord/rayon belt
Hawk	GR70-15	.01469	Rayon cord/steel belt retread
Firestone Town & Country Radial	P175-80R13	.01471	Polyester cord/steel belt mud and snow tread

APPENDIX IV (Cont'd)

Tire	Size	RRC	Comments
BIAS-BELTED (all bias-belted tires in this sample have polyester cord/glass belt)			
Goodyear Cushion Belt Poly Glas	B78-13	.01279	
"	"	.01294	
"	"	.01313	
Delta Custom 78	C78-13	.01324	
Montgomery Ward Runabout Belted	B78-13	.01361	
B.F.Goodrich Belted CLM	P225-75B15	.01380	
Multimile Power King Belted	A78-13	.01390	
B.F.Goodrich Belted CLM	P215-75B15	.01421	
"	P215-75B14	.01440	
Cooper Lifeliner	B78-13	.01463	
General Jumbo Belted	B78-13	.01465	
B.F. Goodrich Belted CLM	P165-80B13	.01506	
Penney El Tigre 278	B78-13	.01543	
Sears Superguard Belted	A78-13	.01598	

APPENDIX IV (Cont'd)

Tire	Size	RRC	Comments
BIAS PLY (all bias ply tires in this sample have polyester body cord unless otherwise stated)			
Goodyear Powerstreak	B78-13	.01291	
"	"	.01292	
"	"	.01304	
"	G78-15	.01320	
Dunlop Gold Seal	B78-13	.01326	
Goodyear Powerstreak	H78-15	.01335	
"	B78-13	.01341	
"	"	.01349	
"	"	.01350	
"	"	.01353	
Montgomery Ward Runabout	B78-13	.01354	
Goodyear Powerstreak	G78-14	.01356	
"	B78-13	.01357	
"	"	.01358	
"	"	.01361	
Kelly Benchmark	B78-13	.01375	
Uniroyal Fastrax	B78-13	.01383	
Sears Dynaply 24	B78-13	.01471	
"	"	.01482	
Firestone Deluxe Champion	B78-13	.01500	
Hercules Saftipreme	B78-13	.01509	
Firestone Deluxe Champion	A78-13	.01517	Rayon cord, retread
"	B78-13	.01536	(polyester cord, non-retread)
Firestone Town & Country	B78-13	.01568	Retread with mud and snow tread
Atlas Cushionaire	B78-13	.01576	
K-Mart KM 78	B78-13	.01582	
Firestone Town & Country	B78-13	.01584	Retread with mud and snow tread

APPENDIX IV (Cont'd)

Tire	Size	RRC	Comments
BIAS PLY (all bias ply tires in this sample have polyester body cord unless otherwise stated)			
Armstrong Power King	B78-13	.01641	
Firestone Deluxe Champion	A78-13	.01695	Retread
Firestone Town & Country	B78-13	.01702	Mud and snow tread
Firestone Deluxe Champion	A78-13	.01714	Rayon cord, retread
Firestone Town & Country	B78-13	.01753	Mud and snow tread
Firestone Deluxe Champion	A78-13	.01754	Rayon cord, retread
Firestone Town & Country	B78-13	.01810	Mud and snow tread

APPENDIX IV (Cont'd)

Tire	Size	RRC	Comments
BIAS-BELTED (all bias-belted tires in this sample have polyester cord/glass belt)			
Goodyear Cushion Belt Poly Glas	B78-13	.01279	
"	"	.01294	
"	"	.01313	
Delta Custom 78	C78-13	.01324	
Montgomery Ward Runabout Belted	B78-13	.01361	
B.F.Goodrich Belted CLM	P225-75B15	.01380	
Multimile Power King Belted	A78-13	.01390	
B.F.Goodrich Belted CLM	P215-75B15	.01421	
"	P215-75B14	.01440	
Cooper Lifeliner	B78-13	.01463	
General Jumbo Belted	B78-13	.01465	
B.F. Goodrich Belted CLM	P165-80B13	.01506	
Penney El Tigre 278	B78-13	.01543	
Sears Superguard Belted	A78-13	.01598	

APPENDIX IV (Cont'd)

Tire	Size	RRC	Comments
RADIAL			
Sears Roadhandler	BR78-13	.01354	Polyester cord/steel belt
Hawk	GR70-15	.01454	Polyester cord/steel belt retread
B.F. Goodrich T/A Mark	P175-70R13	.01462	Rayon cord/rayon belt
Hawk	GR70-15	.01469	Rayon cord/steel belt retread
Firestone Town & Country Radial	P175-80R13	.01471	Polyester cord/steel belt mud and snow tread

APPENDIX IV (Cont'd)

Tire	Size	RRC	Comments
BIAS PLY (all bias ply tires in this sample have polyester body cord unless otherwise stated)			
Goodyear Powerstreak	B78-13	.01291	
"	"	.01292	
"	"	.01304	
"	G78-15	.01320	
Dunlop Gold Seal	B78-13	.01326	
Goodyear Powerstreak	H78-15	.01335	
"	B78-13	.01341	
"	"	.01349	
"	"	.01350	
"	"	.01353	
Montgomery Ward Runabout	B78-13	.01354	
Goodyear Powerstreak	G78-14	.01356	
"	B78-13	.01357	
"	"	.01358	
"	"	.01361	
Kelly Benchmark	B78-13	.01375	
Uniroyal Fastrax	B78-13	.01383	
Sears Dynaply 24	B78-13	.01471	
"	"	.01482	
Firestone Deluxe Champion	B78-13	.01500	
Hercules Saftipreme	B78-13	.01509	
Firestone Deluxe Champion	A78-13	.01517	Rayon cord, retread
"	B78-13	.01536	(polyester cord, non-retread)
Firestone Town & Country	B78-13	.01568	Retread with mud and snow tread
Atlas Cushionaire	B78-13	.01576	
K-Mart KM 78	B78-13	.01582	
Firestone Town & Country	B78-13	.01584	Retread with mud and snow tread

APPENDIX IV (Cont'd)

Tire	Size	RRC	Comments
BIAS PLY (all bias ply tires in this sample have polyester body cord unless otherwise stated)			
Armstrong Power King	B78-13	.01641	
Firestone Deluxe Champion	A78-13	.01695	Retread
Firestone Town & Country	B78-13	.01702	Mud and snow tread
Firestone Deluxe Champion	A78-13	.01714	Rayon cord, retread
Firestone Town & Country	B78-13	.01753	Mud and snow tread
Firestone Deluxe Champion	A78-13	.01754	Rayon cord, retread
Firestone Town & Country	B78-13	.01810	Mud and snow tread

Appendix V

Data and Data Reduction for Each of 106 Tires Tested

This appendix is too voluminous to be included in every copy of this paper. If a copy of this appendix is desired, contact:

EPA/MVEL Library
2565 Plymouth Road
Ann Arbor, Michigan 48105

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